THEIA
Microarcsecond Astrometric Observatory

Pushing the Limits of Astrometry: Technological Advances and Scientific Prospects

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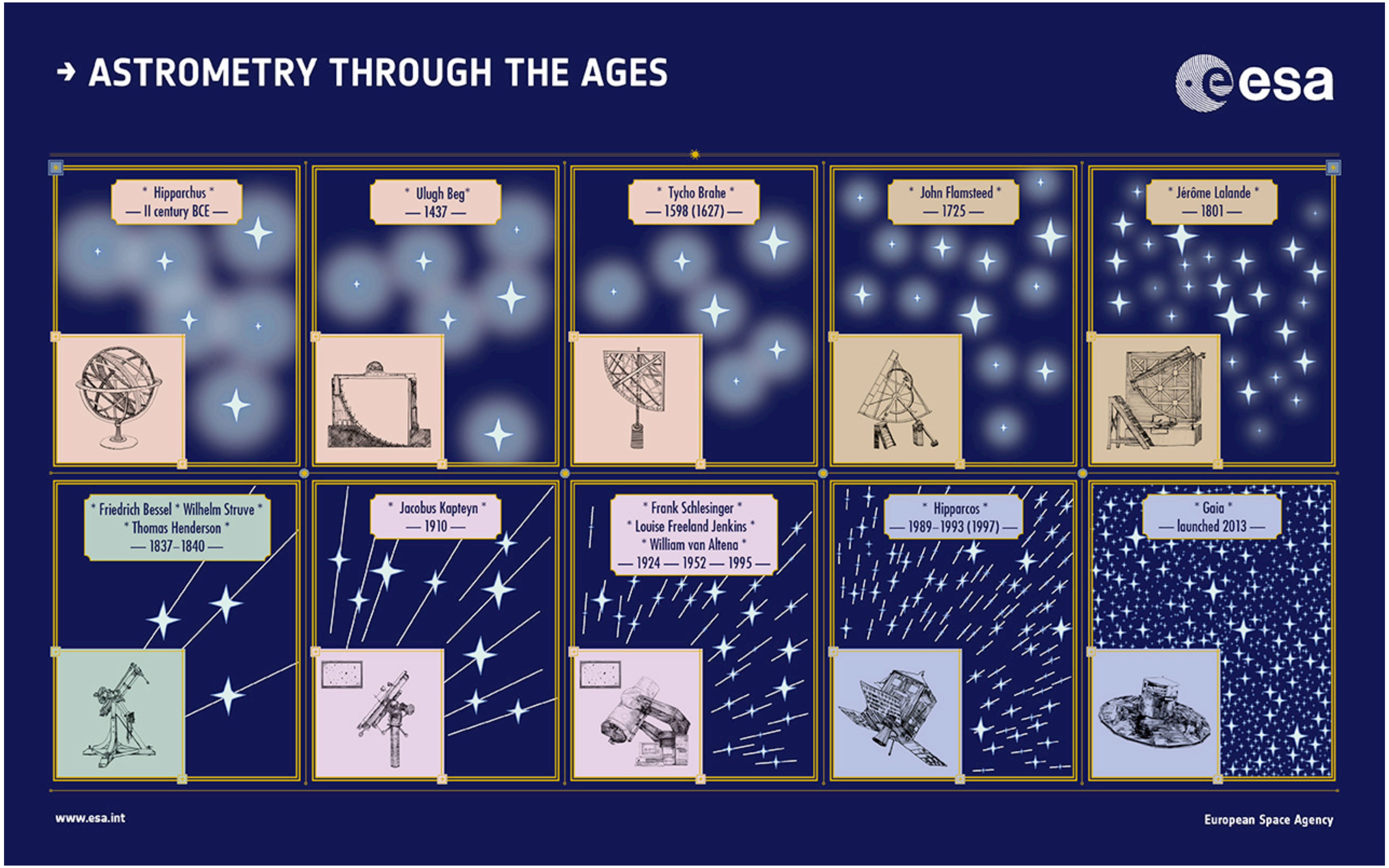
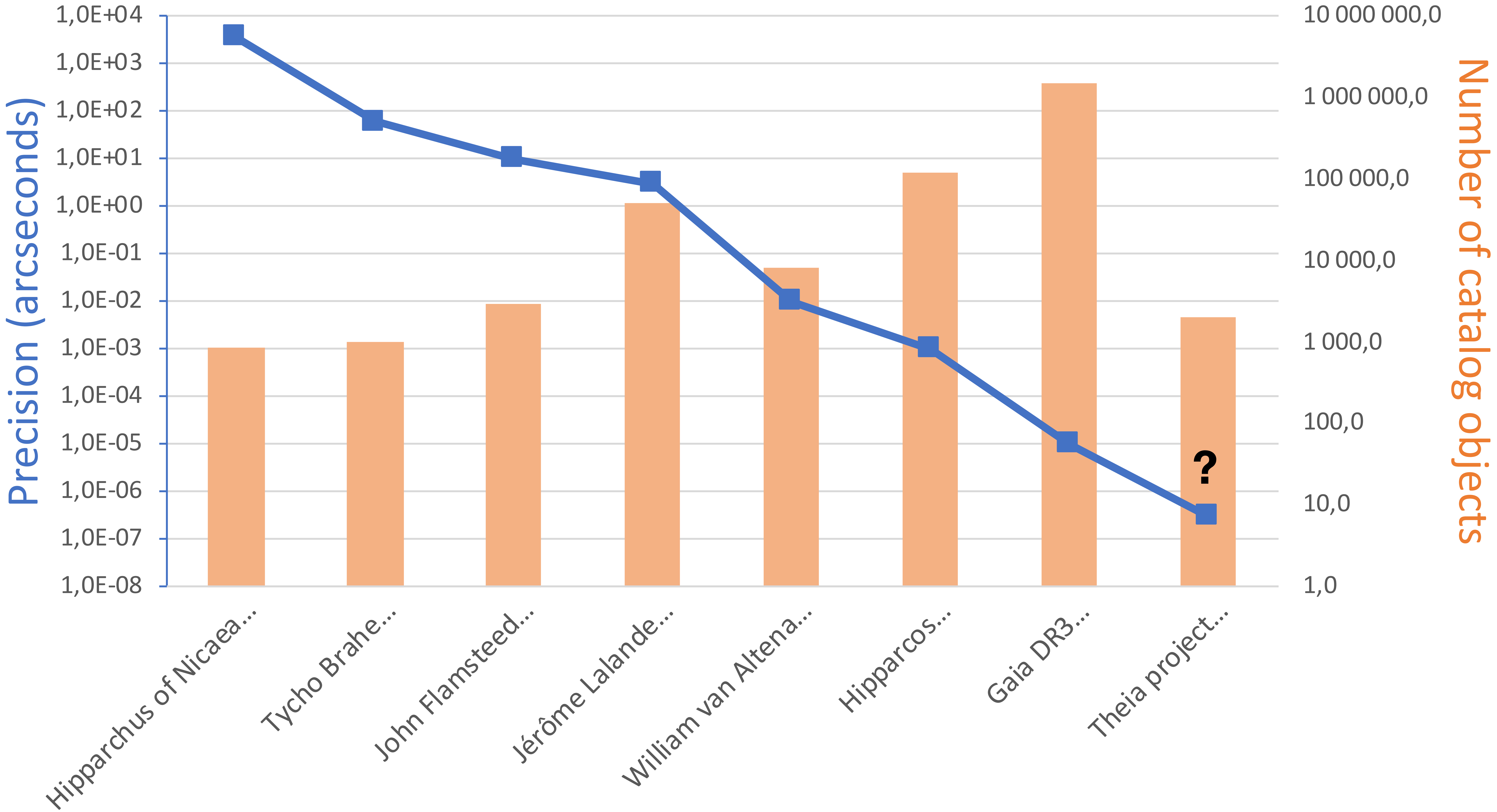
Workshop on « ***A future space mission with very-high precision astrometry*** » - *Paris 11-13 September 2024*

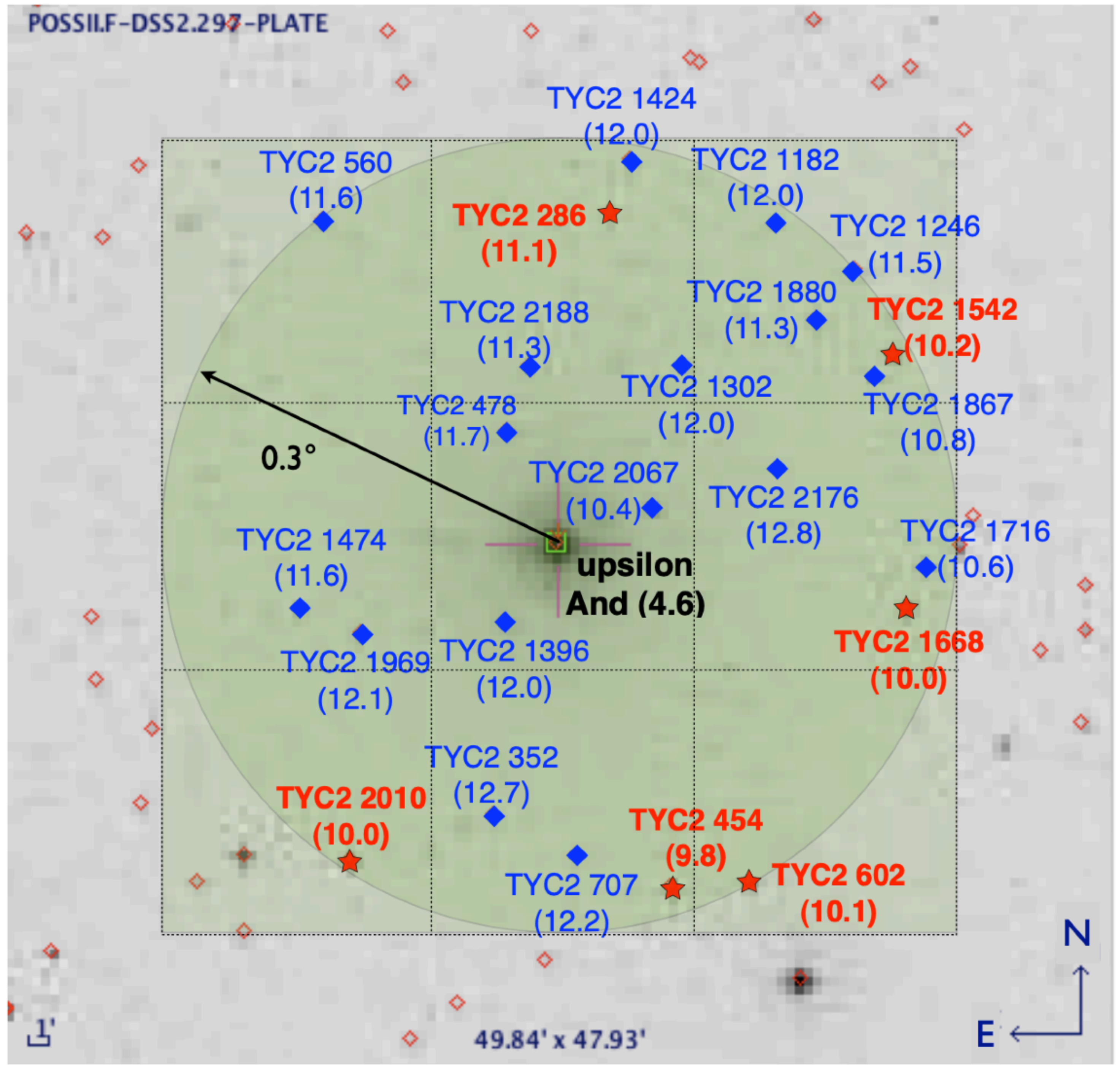
Astrometry : oldest branch of astronomy



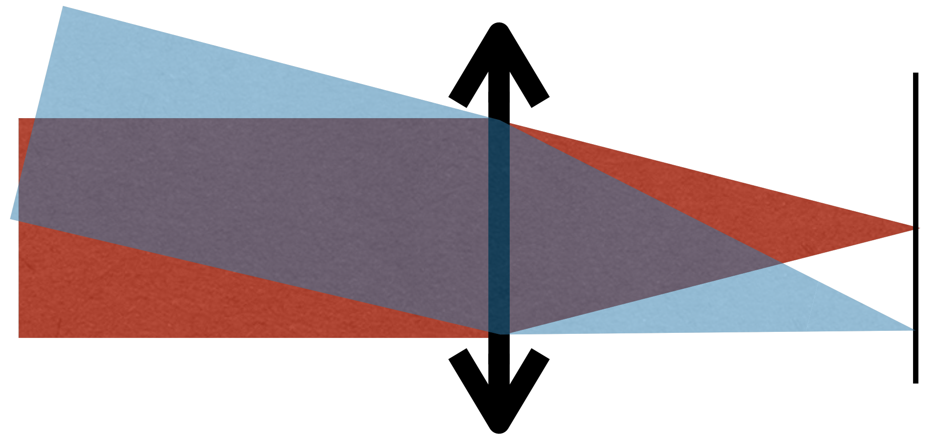
Astrometry precision through the ages

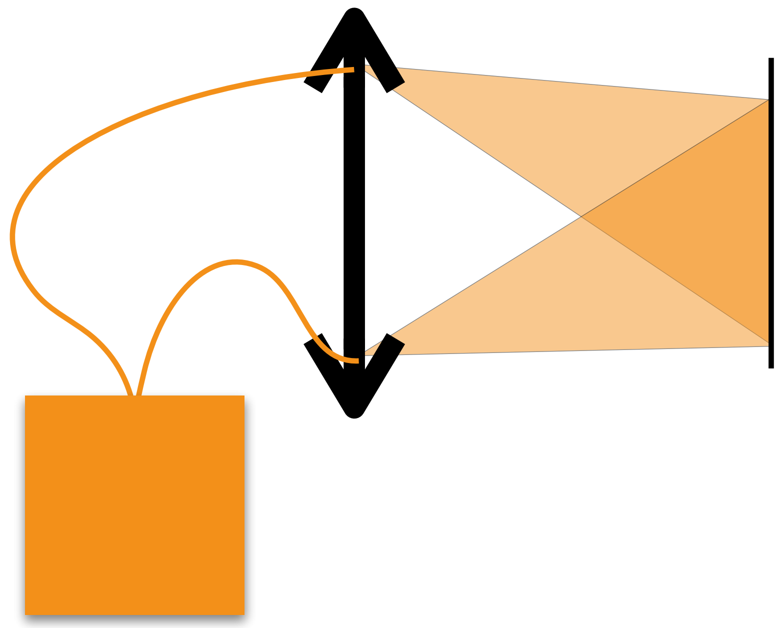


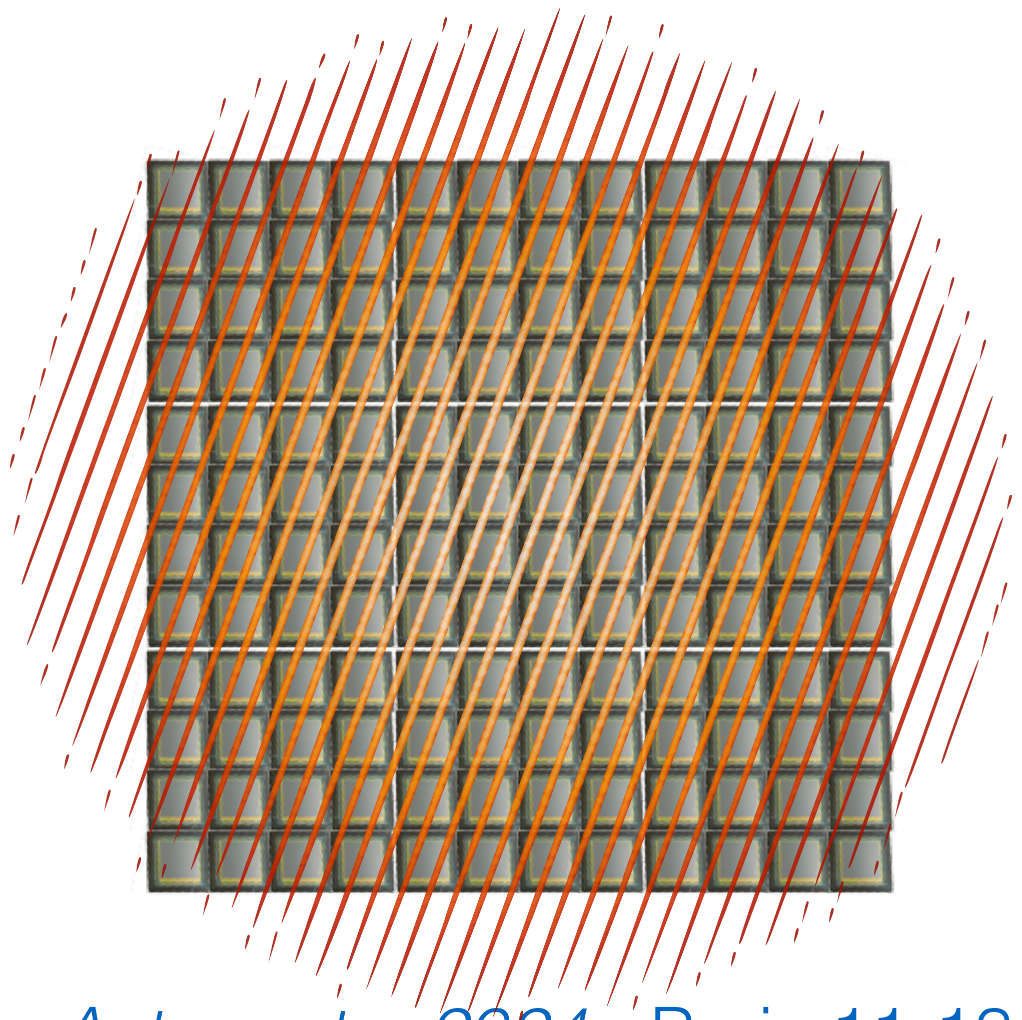
Principle of Theia : relative and precise differential astrometry



- ✓ The science target is at the center of the FOV
- ✓ We measure the offset angles between the target object (in **black**) and the reference stars (other stars in **red** and **blue**)
- ✓ The single measurement is repeated several times over the mission lifetime to reach the required accuracy on the target motion
- ✓ The detector calibration is done using interferometric modulated Young's fringes

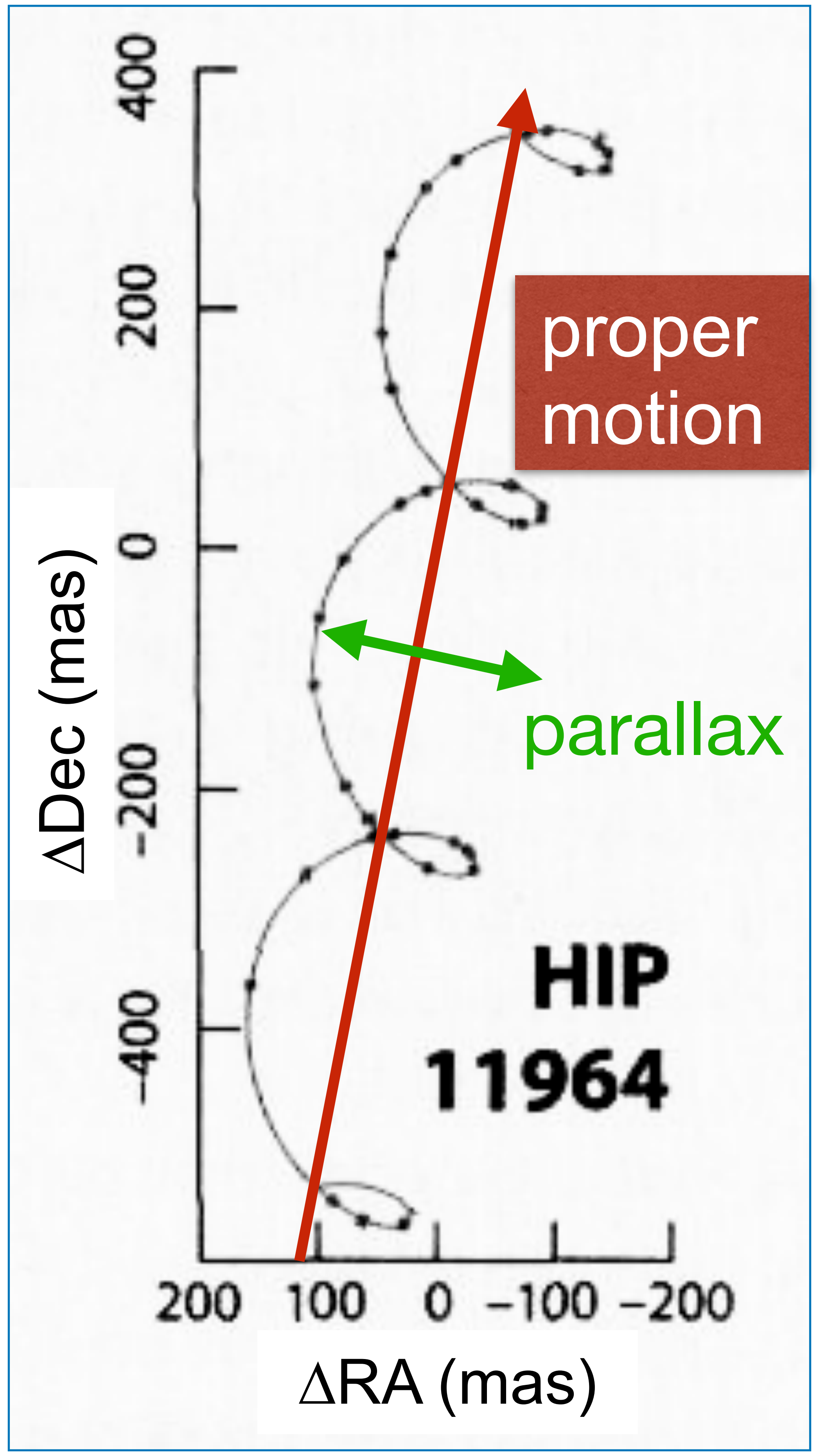


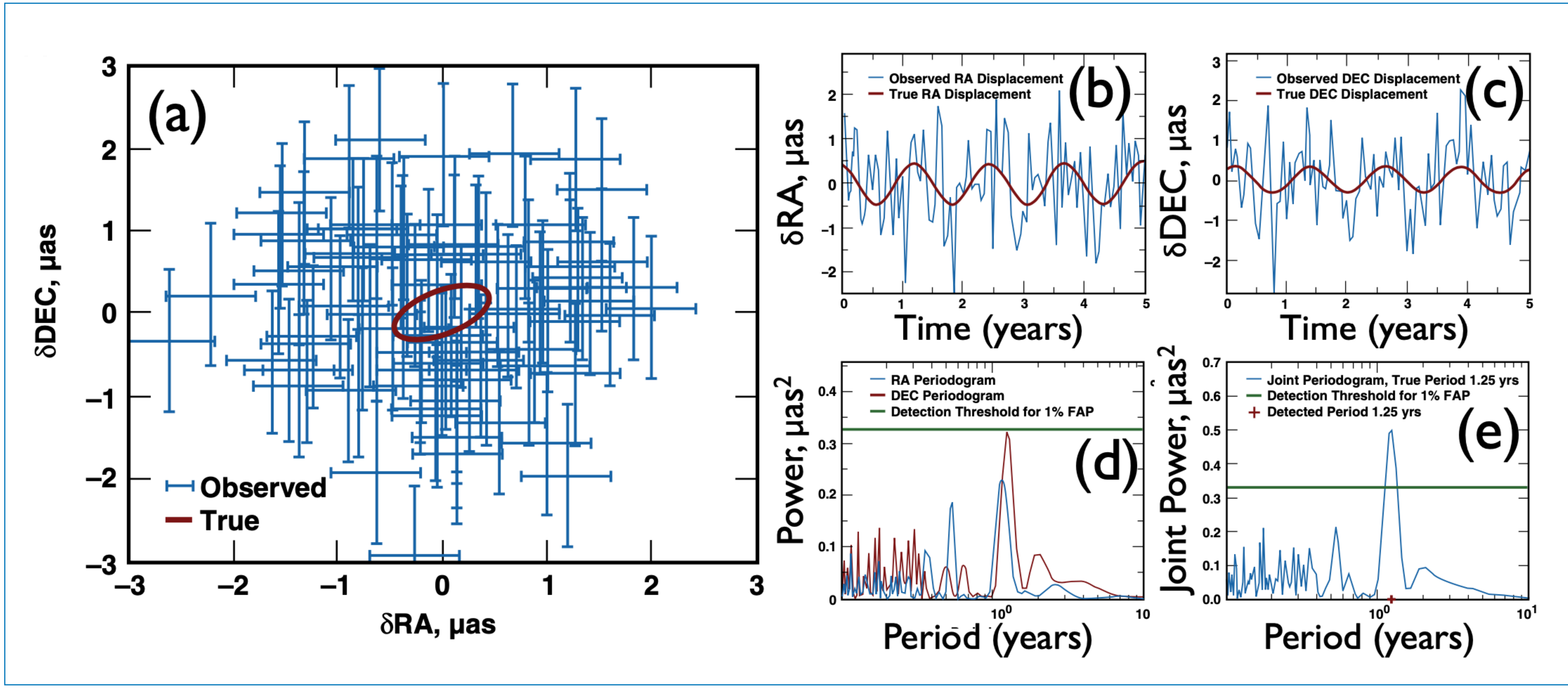




Astrometry: parallax, proper motion and reflex motion

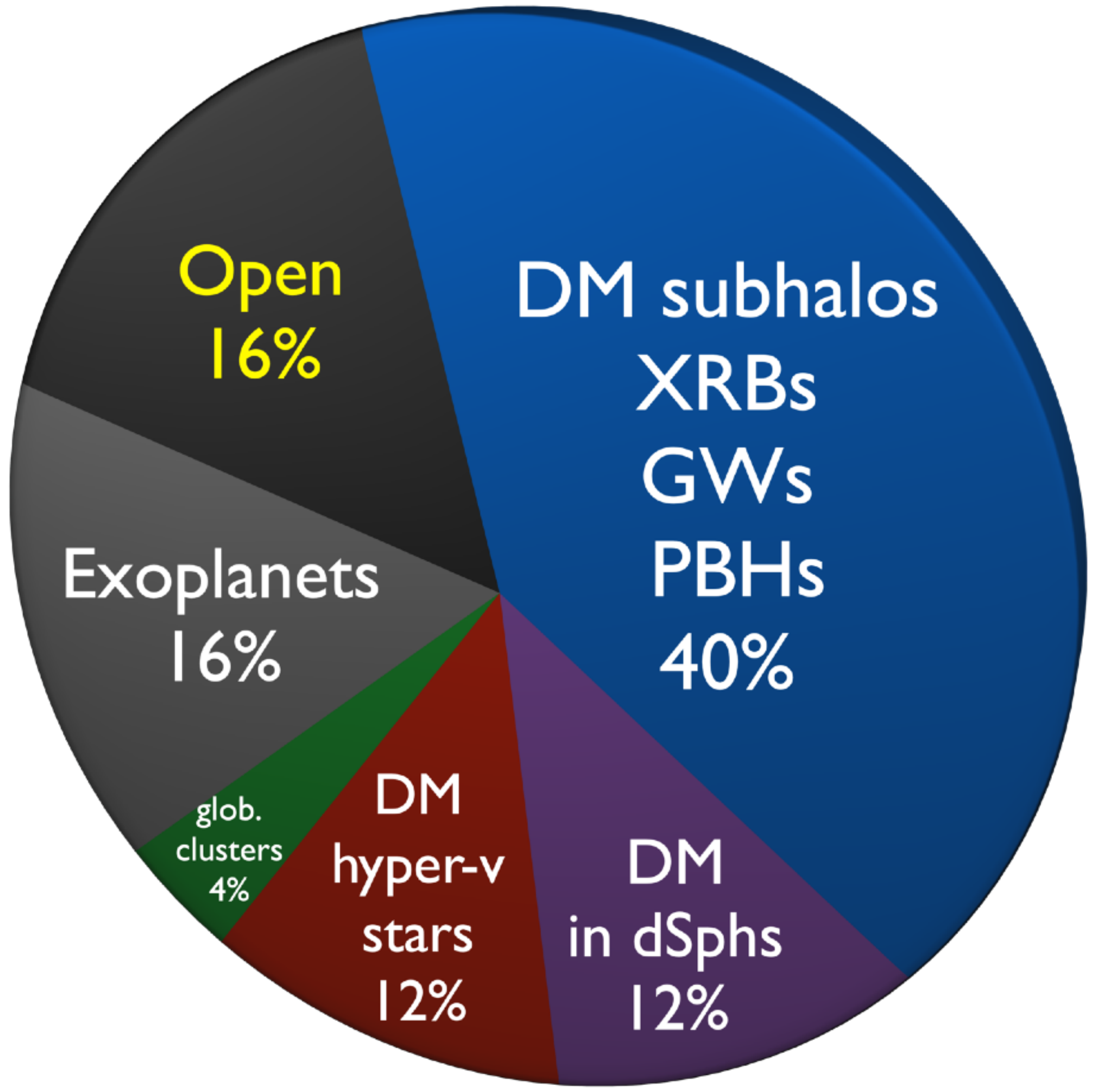
Proper Motion + Parallax ➡ **Residuals where (a) plots RA and DEC positions while (b,c) are positions with time and (d, e) are period-gram for each direction**

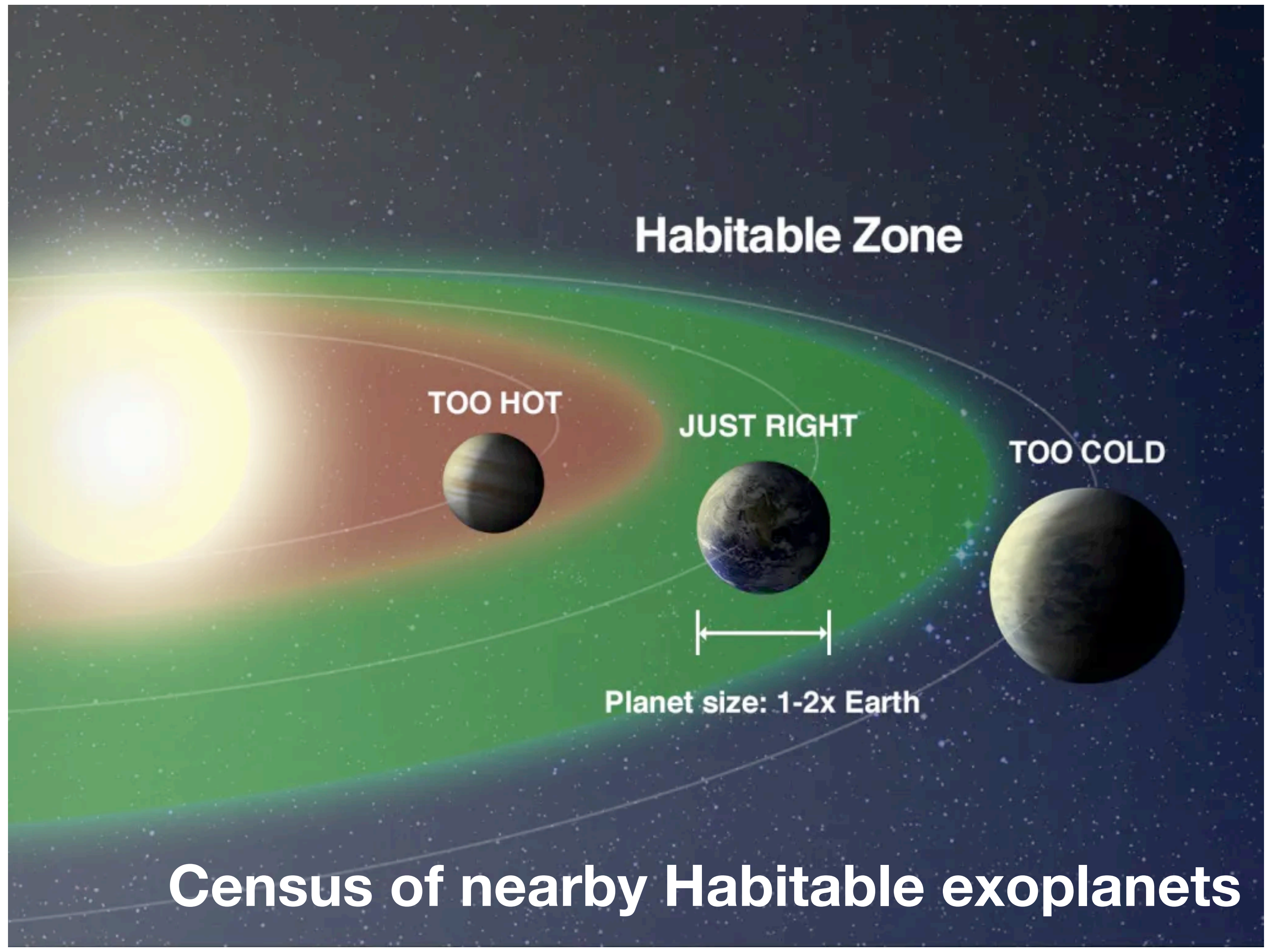




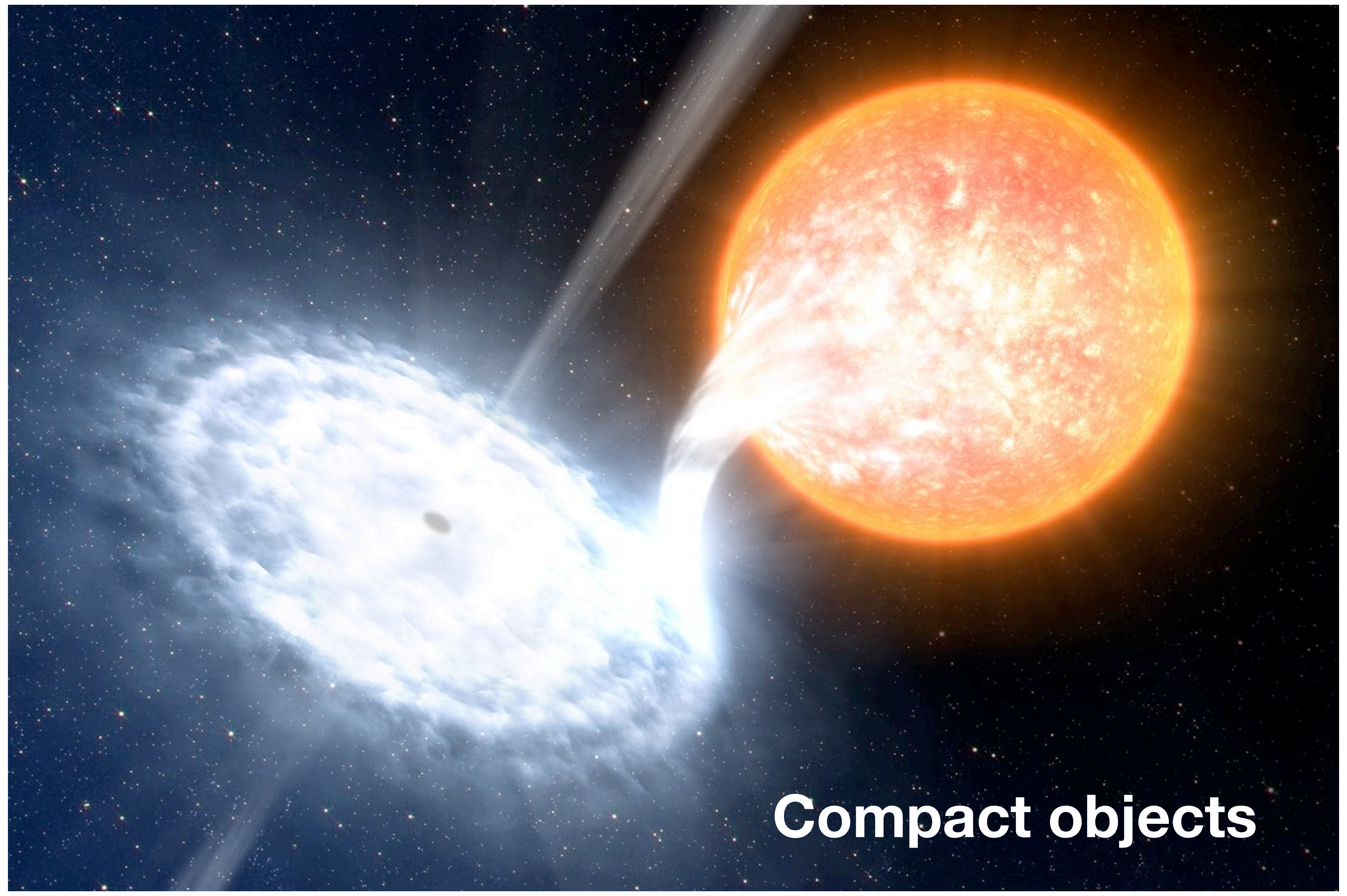
Unwin et al. (2008) ; Malbet et al. (2012)

Theia's main science based on high precision astrometry



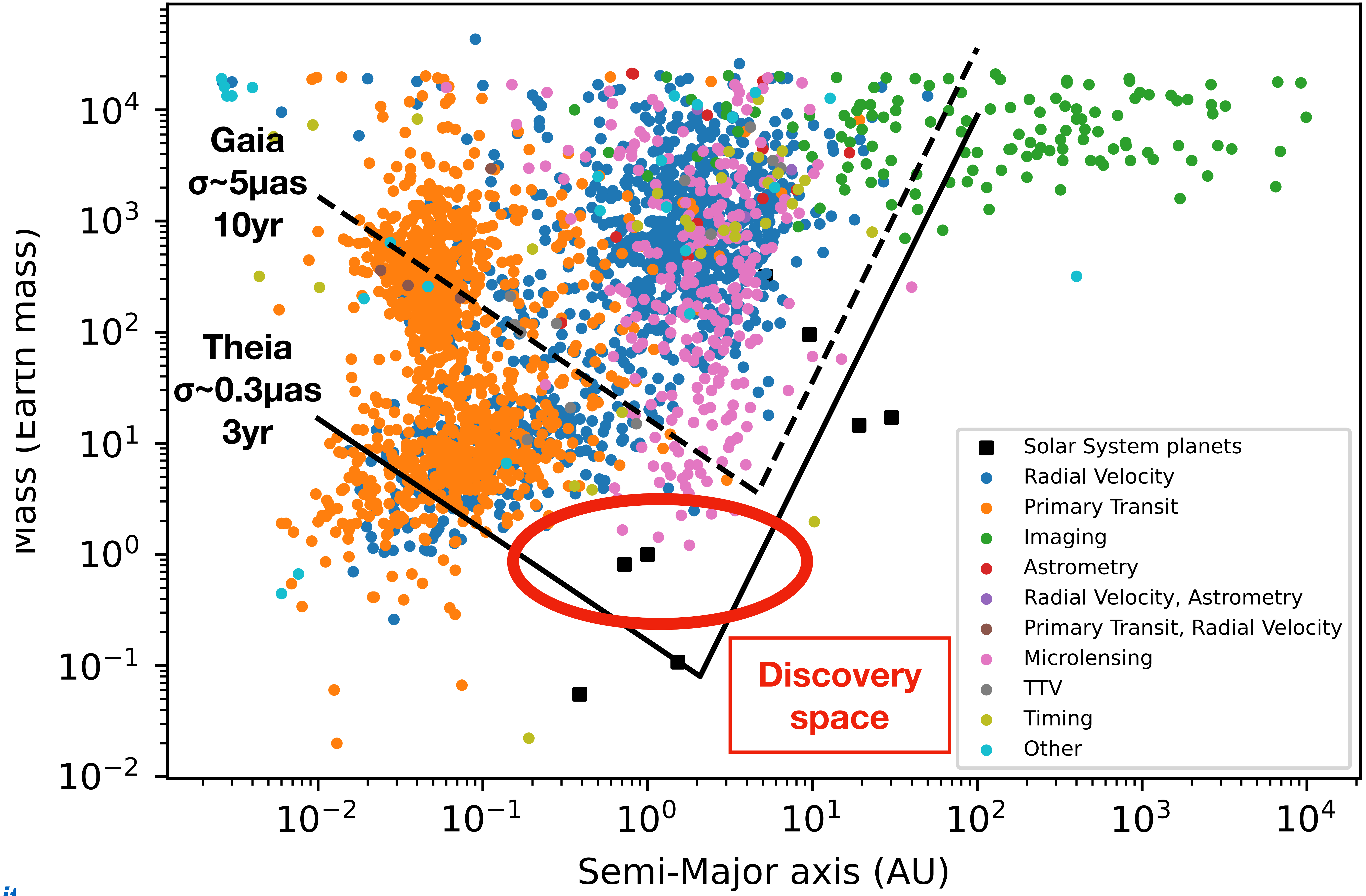


Two main observing modes:
- Faint star mode
- Bright star mode

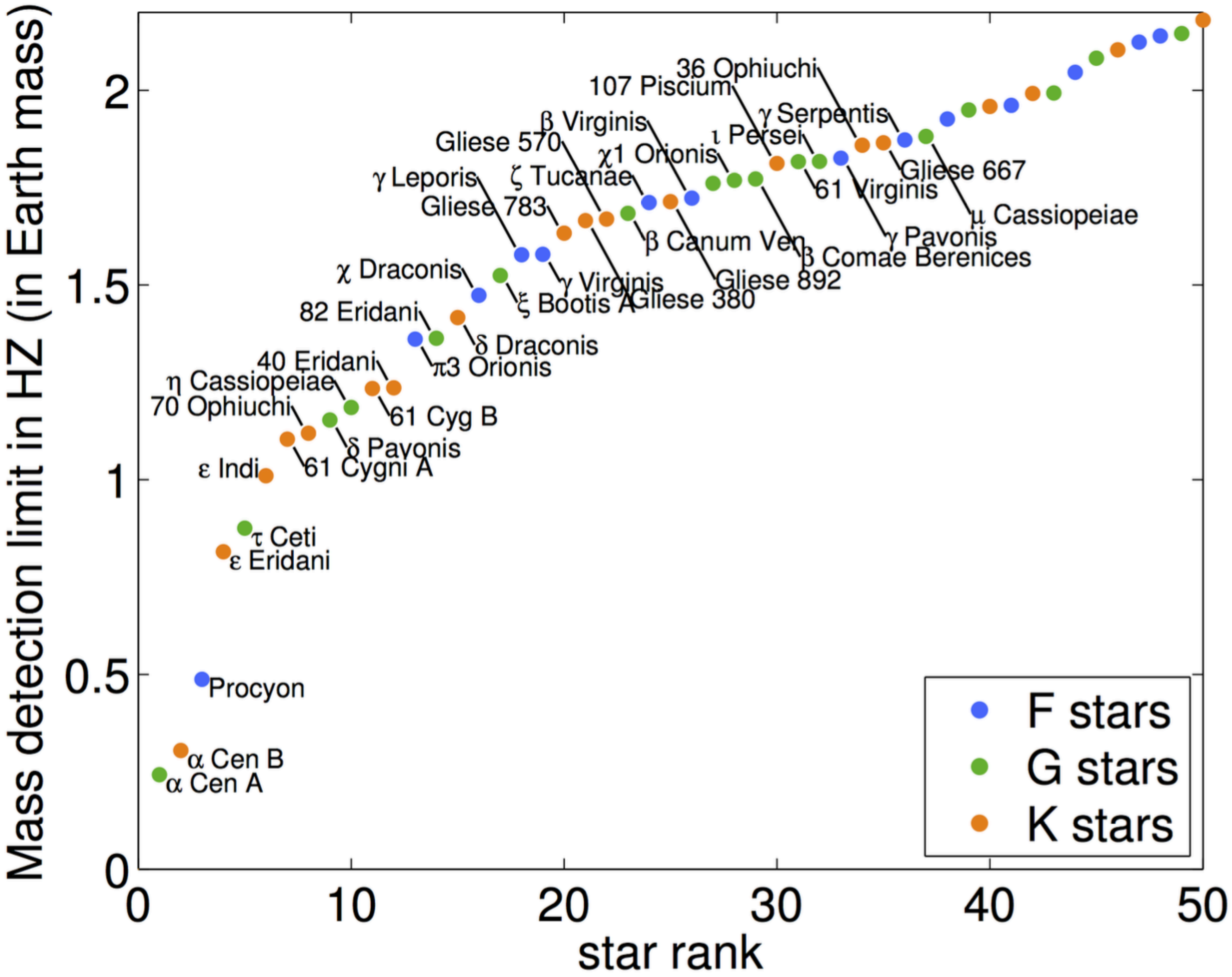


Exoplanets discovery space

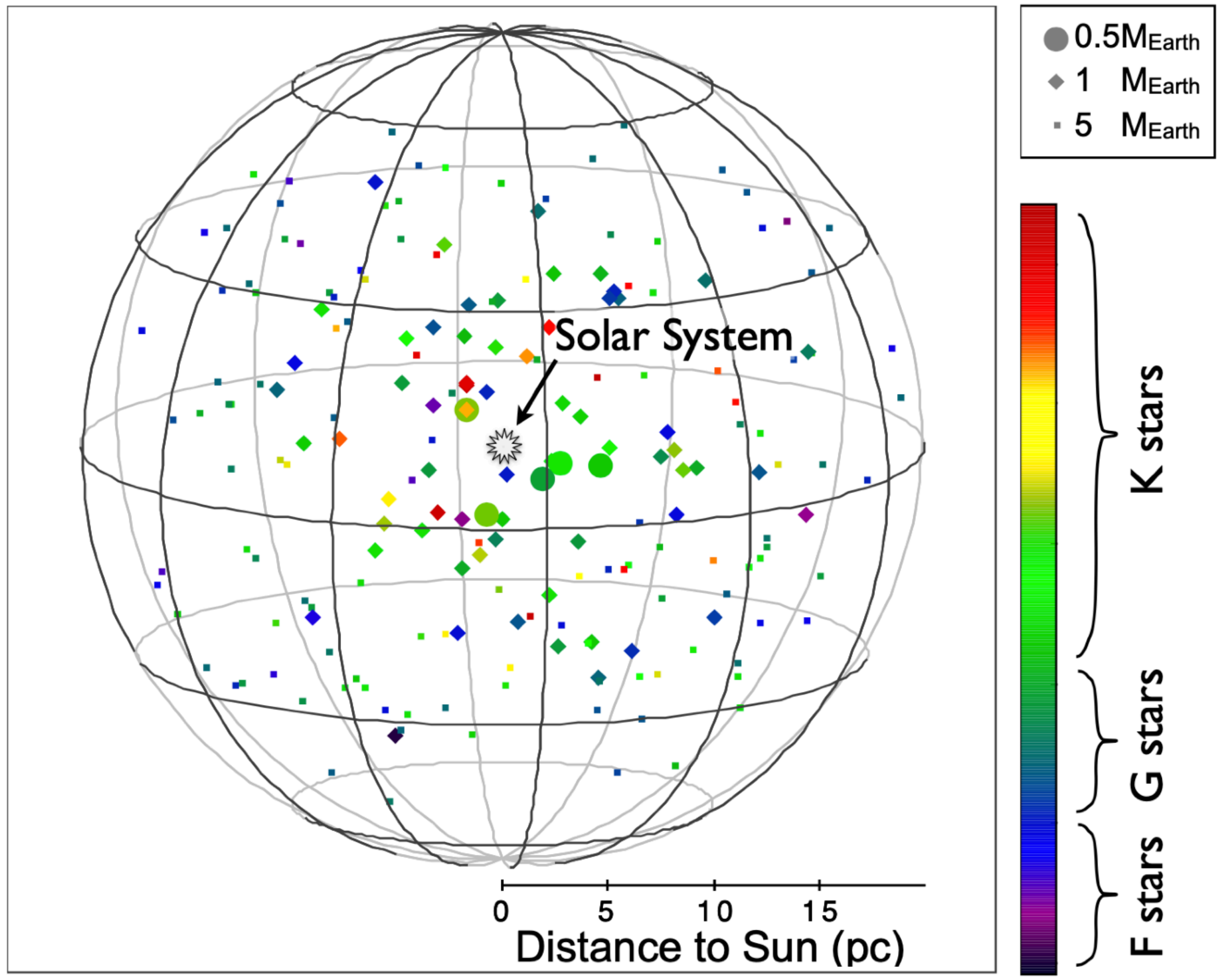
Mass vs Semi-Major Axis Diagram (from exoplanet.eu)



Exoplanets primary goal : Earth-mass planets in HZ in the vicinity of the Sun



Complete census of exo-Earths, superEarths and mini-Neptune (M< 5 M_Earth) orbiting our 50 nearest Solar-type stars (d<10pc)



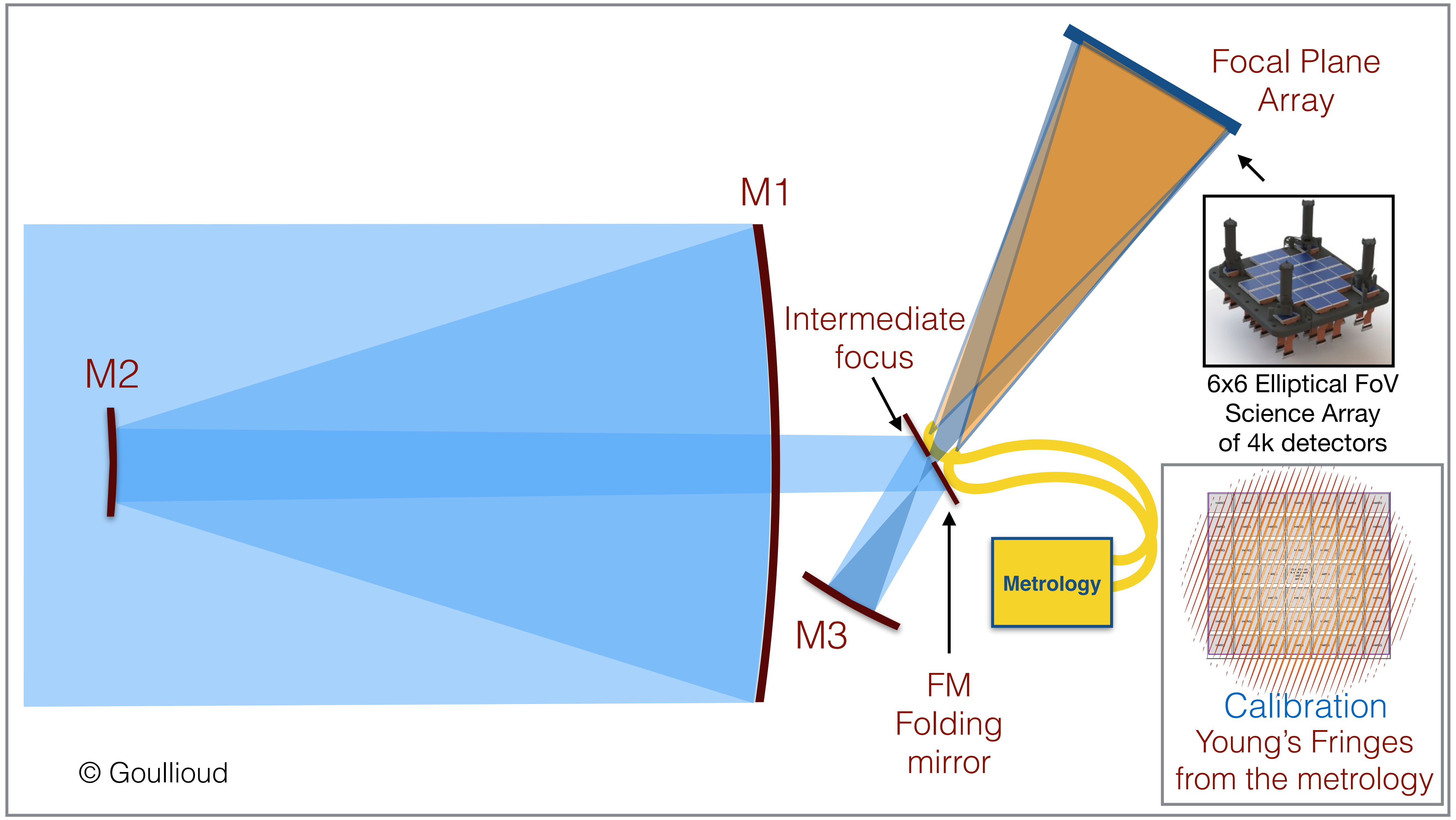
Theia instrumental concept

Specifications:

Diffraction-limited 0.5° FOV

~ 30,000 x 30,000 pixels
≤ 1 billion pixels

Proposed implementation (M7)



But new large CMOS detectors with smaller pixels !

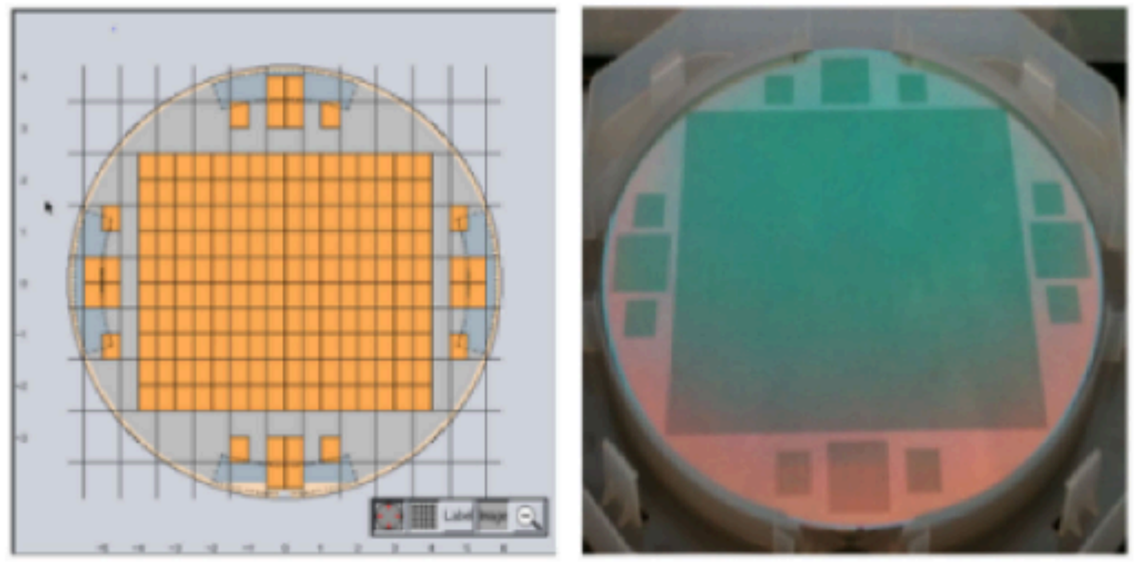


Fig. 14. A huge area, 203 mm × 179 mm, 1.8 Billion pixels CIS (Left: A photograph of the exposure shot map placement and the sensor fabricated on 12 inch; Right: the corresponding wafer image.)

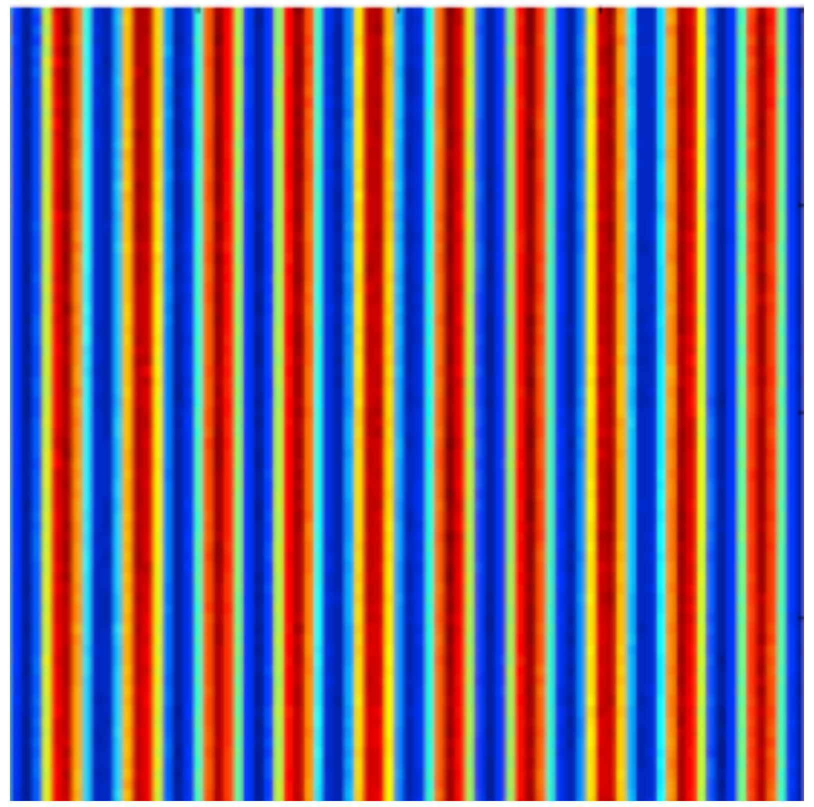
Zhu et al. (2016)

Pixels of ~4μm
=> array of 12 cm x 12 cm,

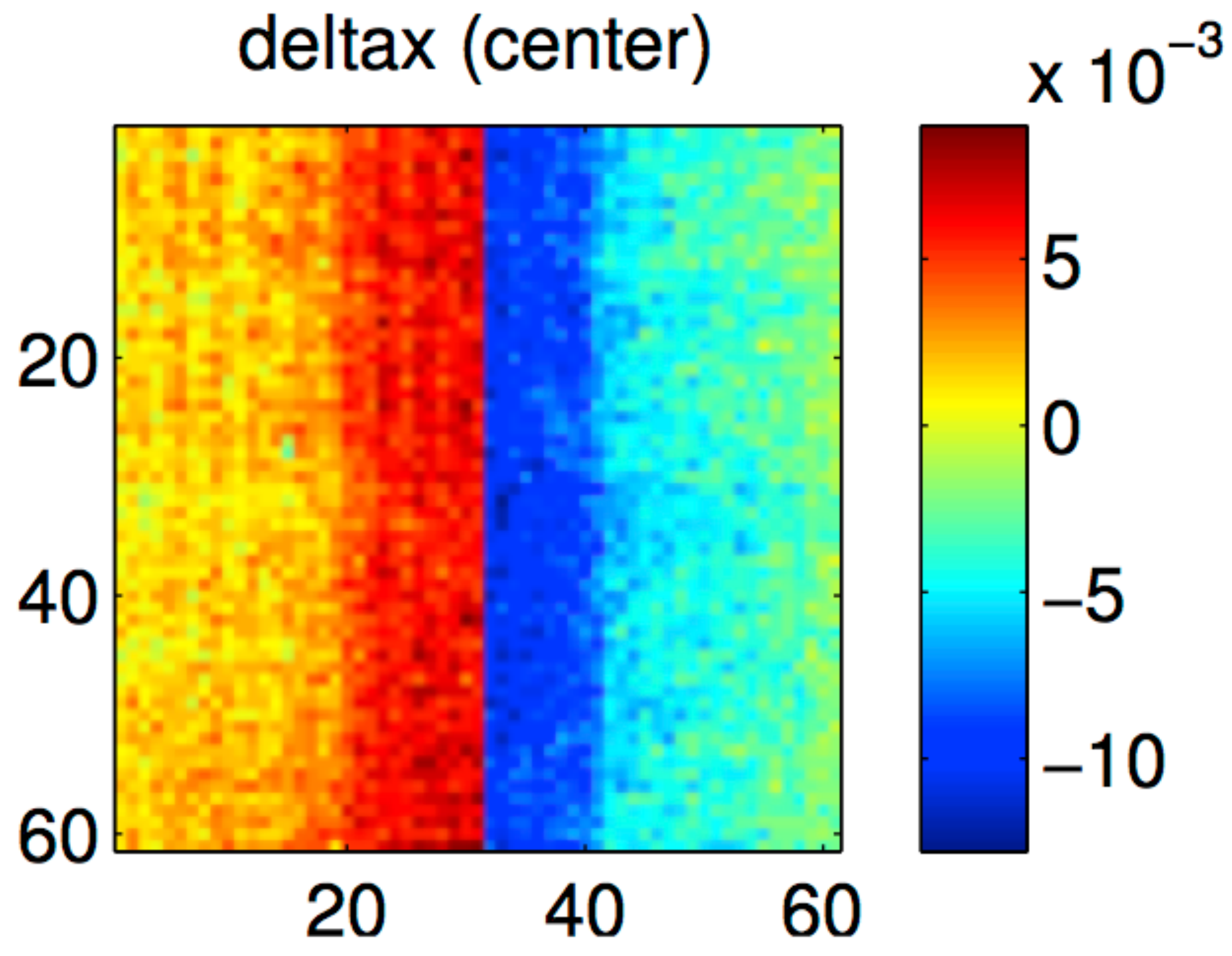
(ie. 30k x 30k detector)

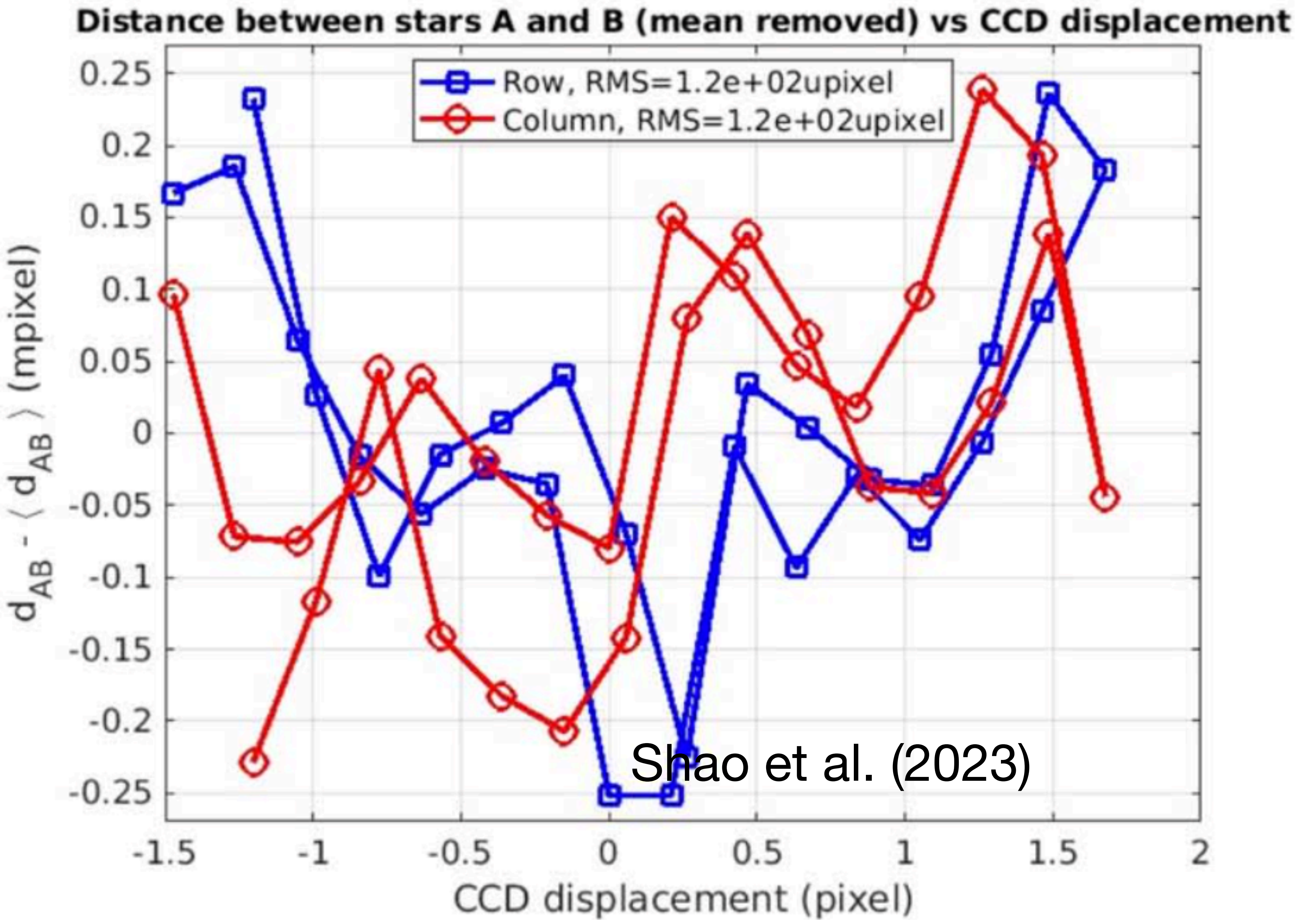
can be manufactured on a wafer of 12" (300mm)

Detector calibration: laboratory results

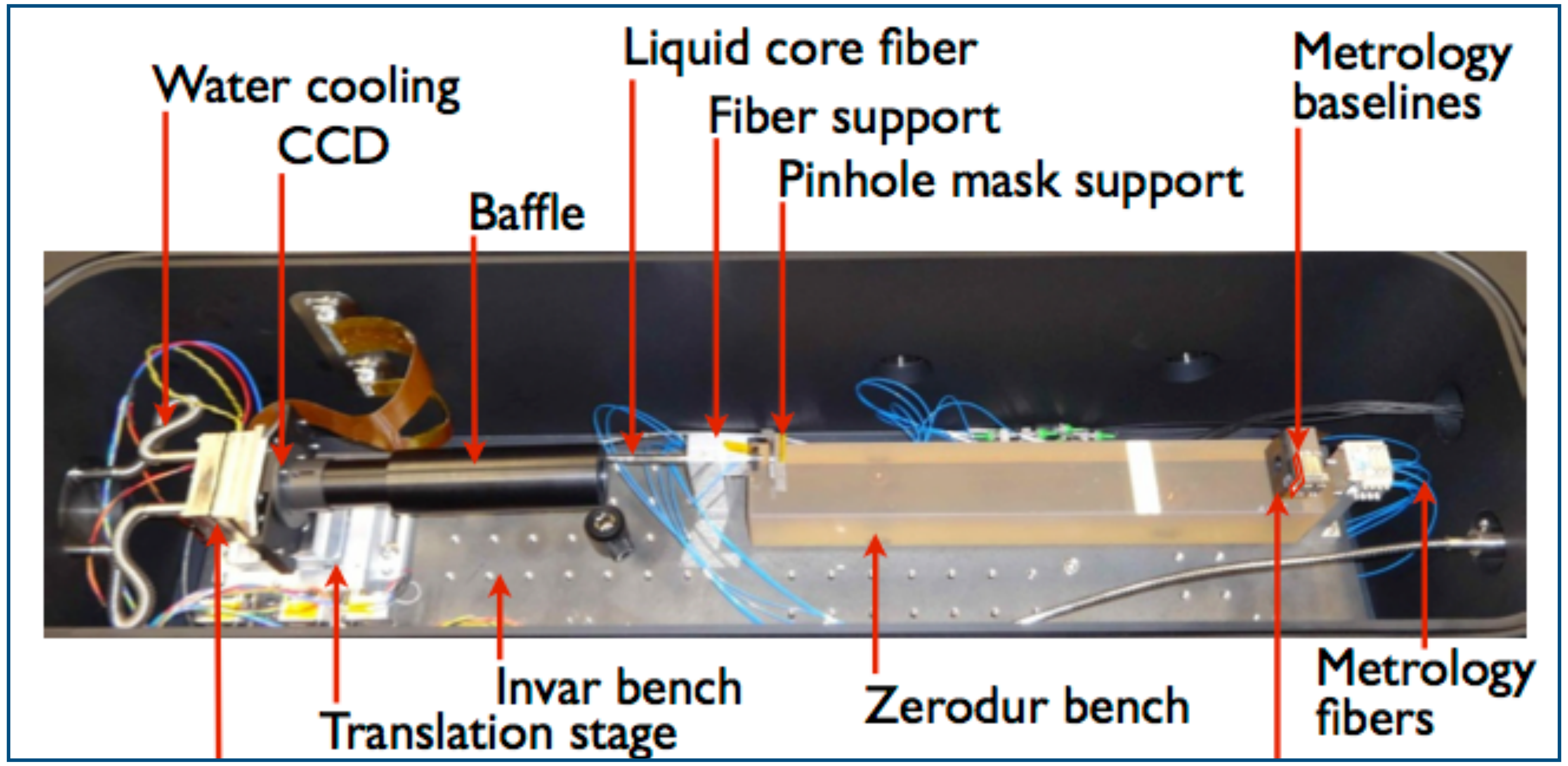


Crouzier et al. (2016)





Shao et al. (2023)

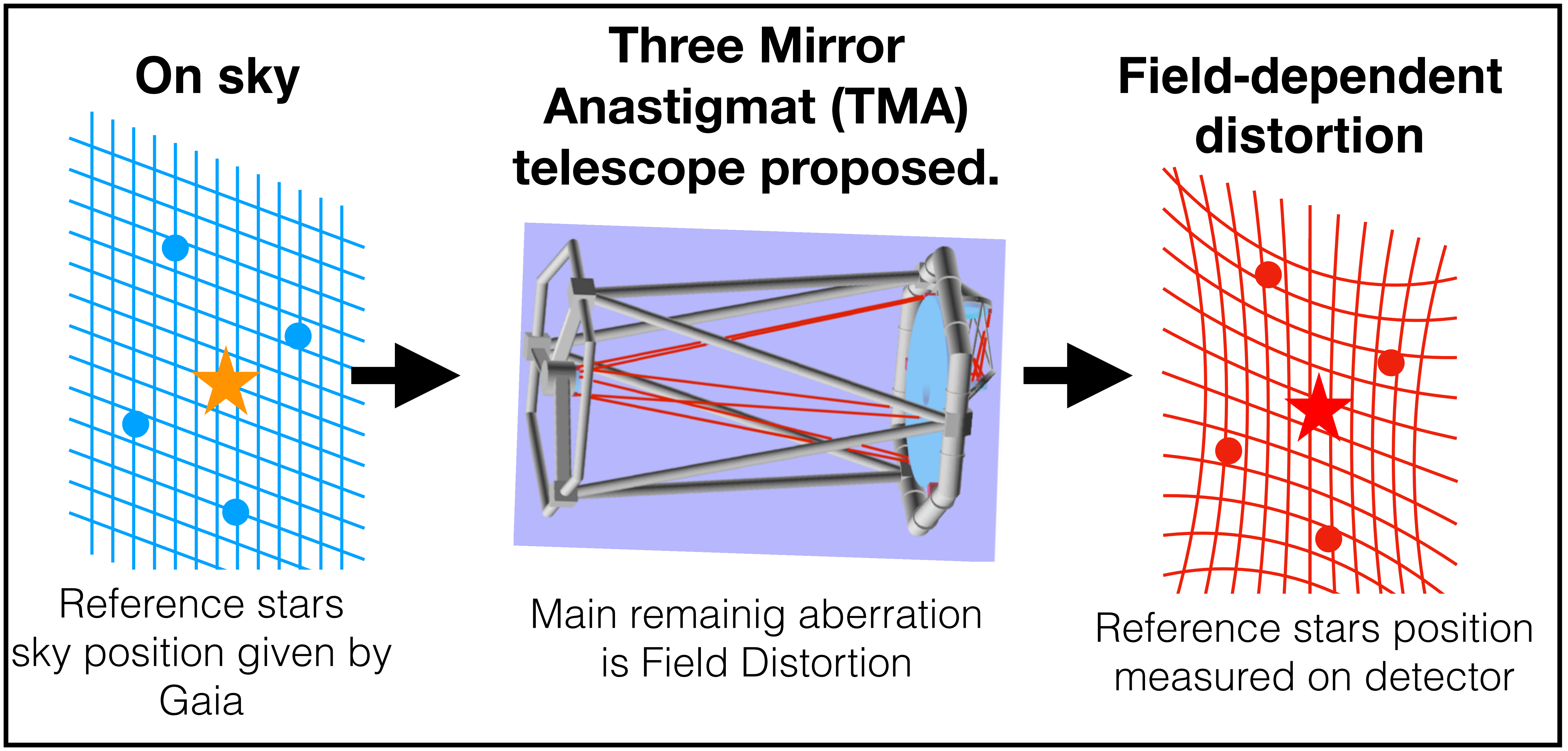


Crouzier et al. (2016)

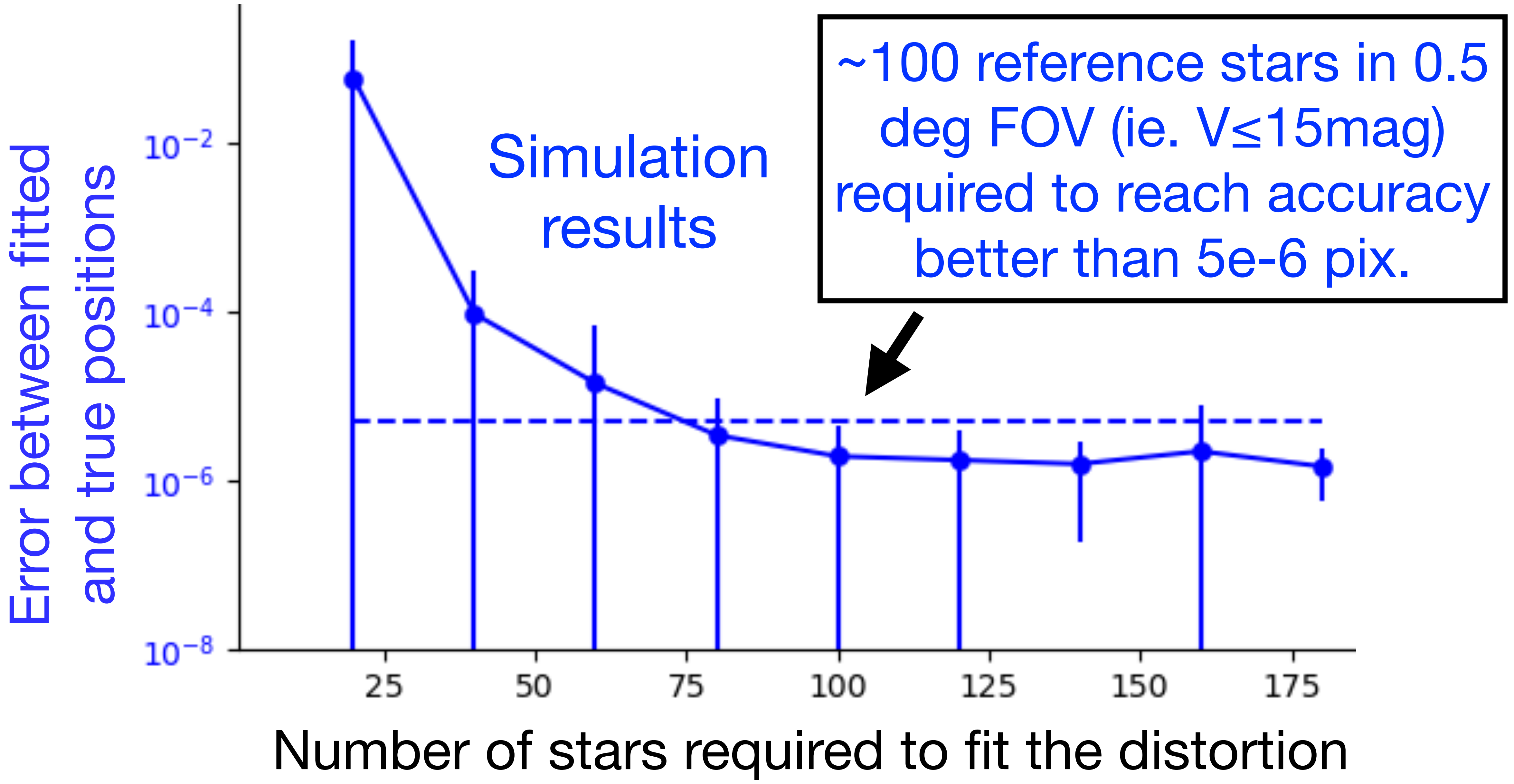
Best results so far:

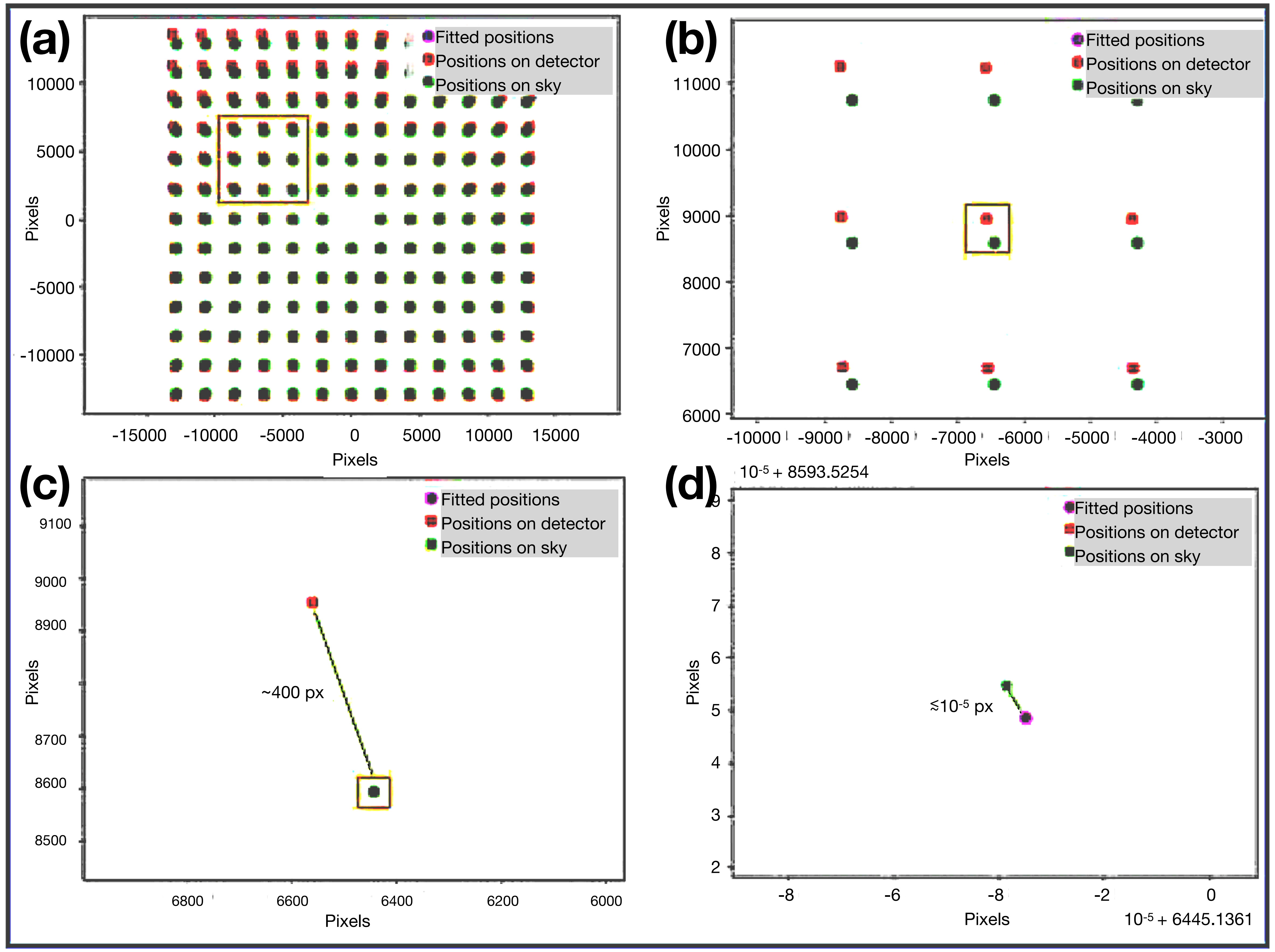
- IPAG/CNES: 6 10^{-5} pixels (Crouzier et al. 2016)
- JPL/VESTA: 3 10^{-5} pixels (Shao et al. 2023)

Telescope calibration : using reference stars to monitor the distortion



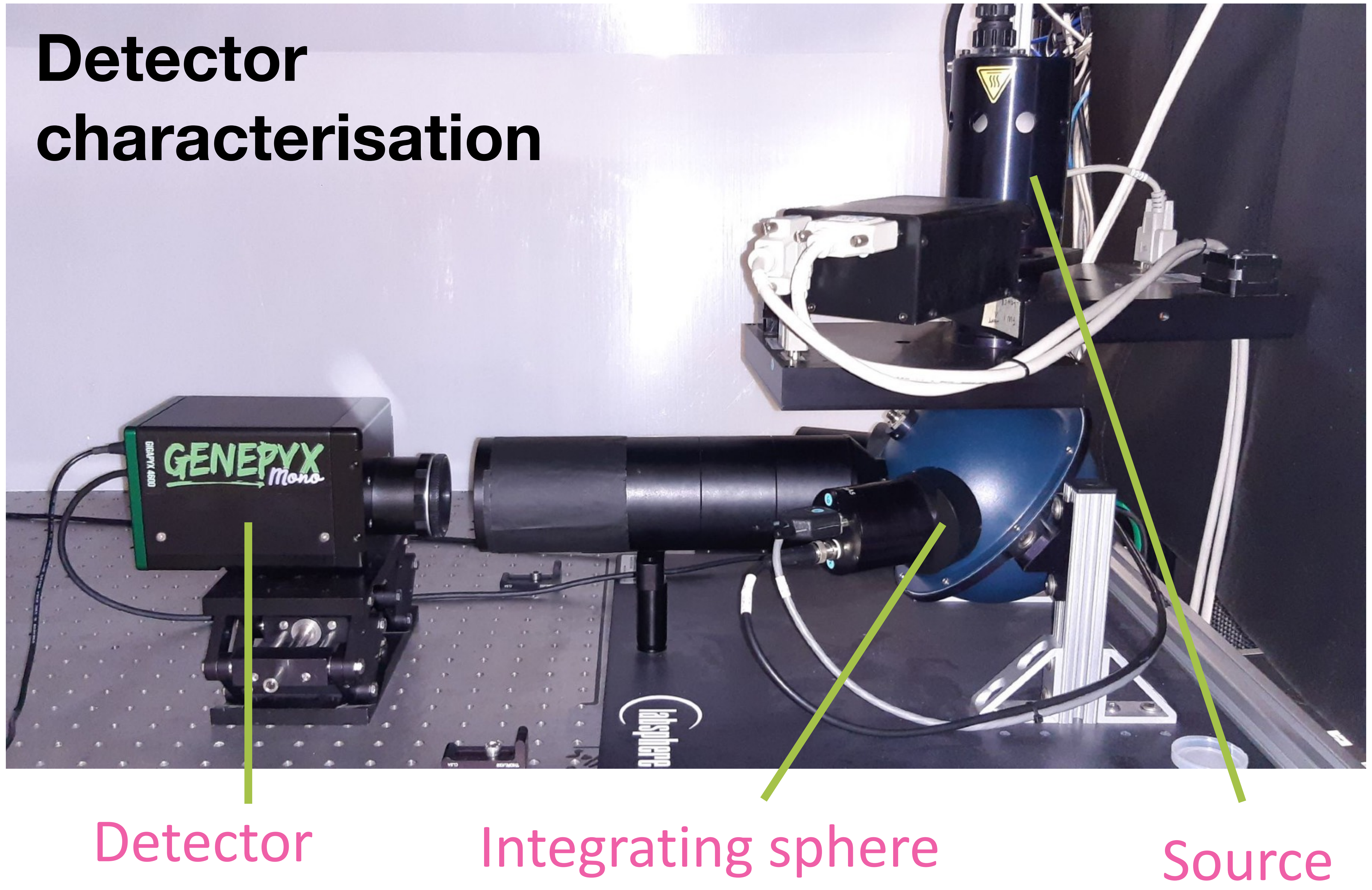
Distortion can be corrected by fitting the transformation (Sky -> Detector) as calculated by Ray-tracing (Zemax) by a 2D polynomial

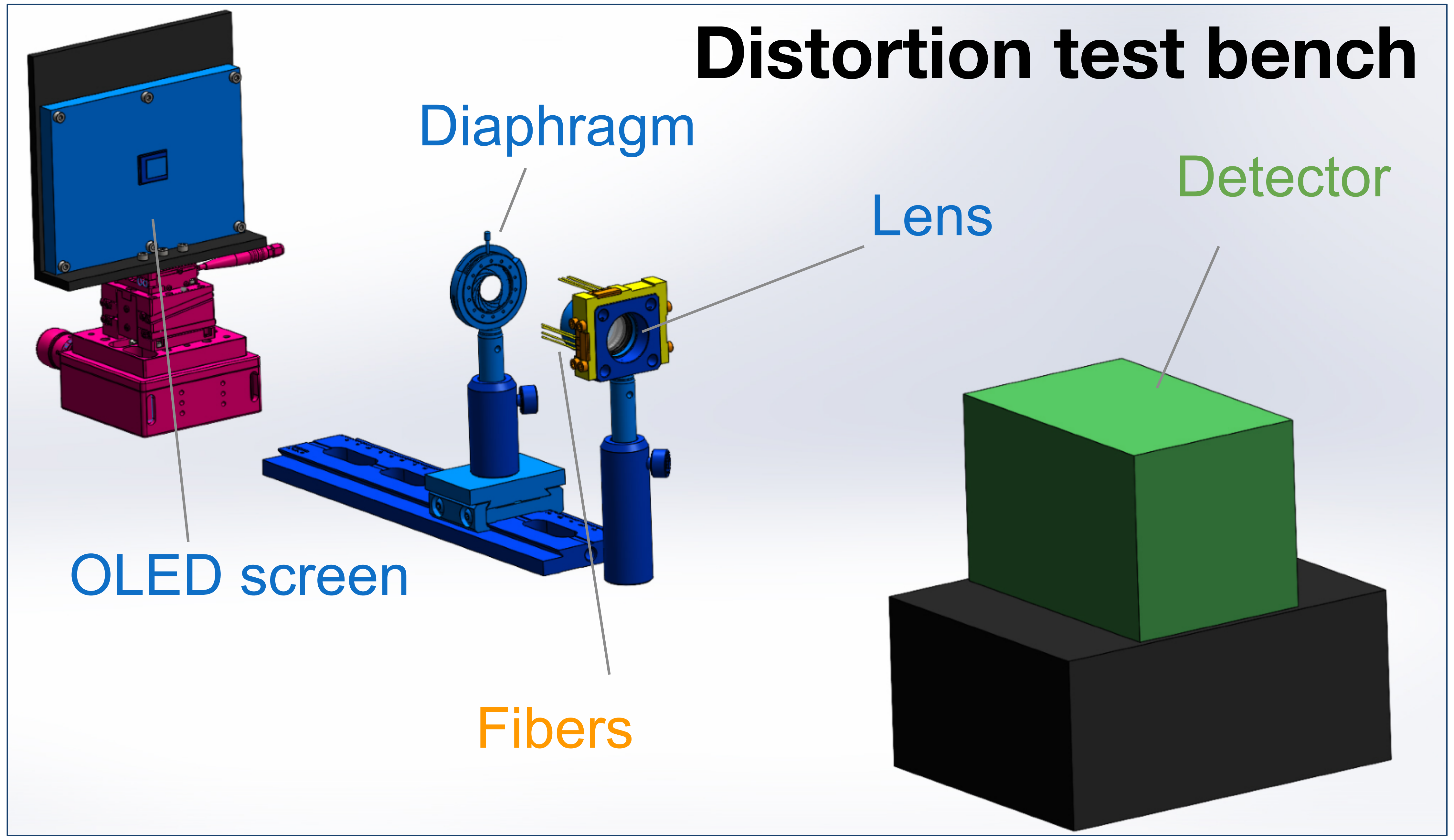




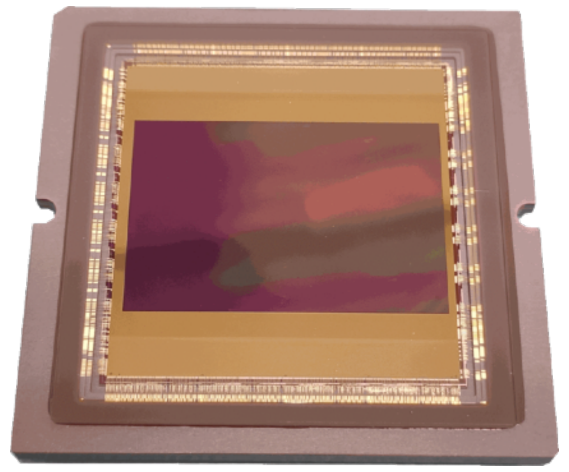
Simulated field-dependent distortion and fitted position

Ongoing test benches at IPAG





GIGAPYX 4600
8320 x 5436
Pixel : 4,4µm pitch

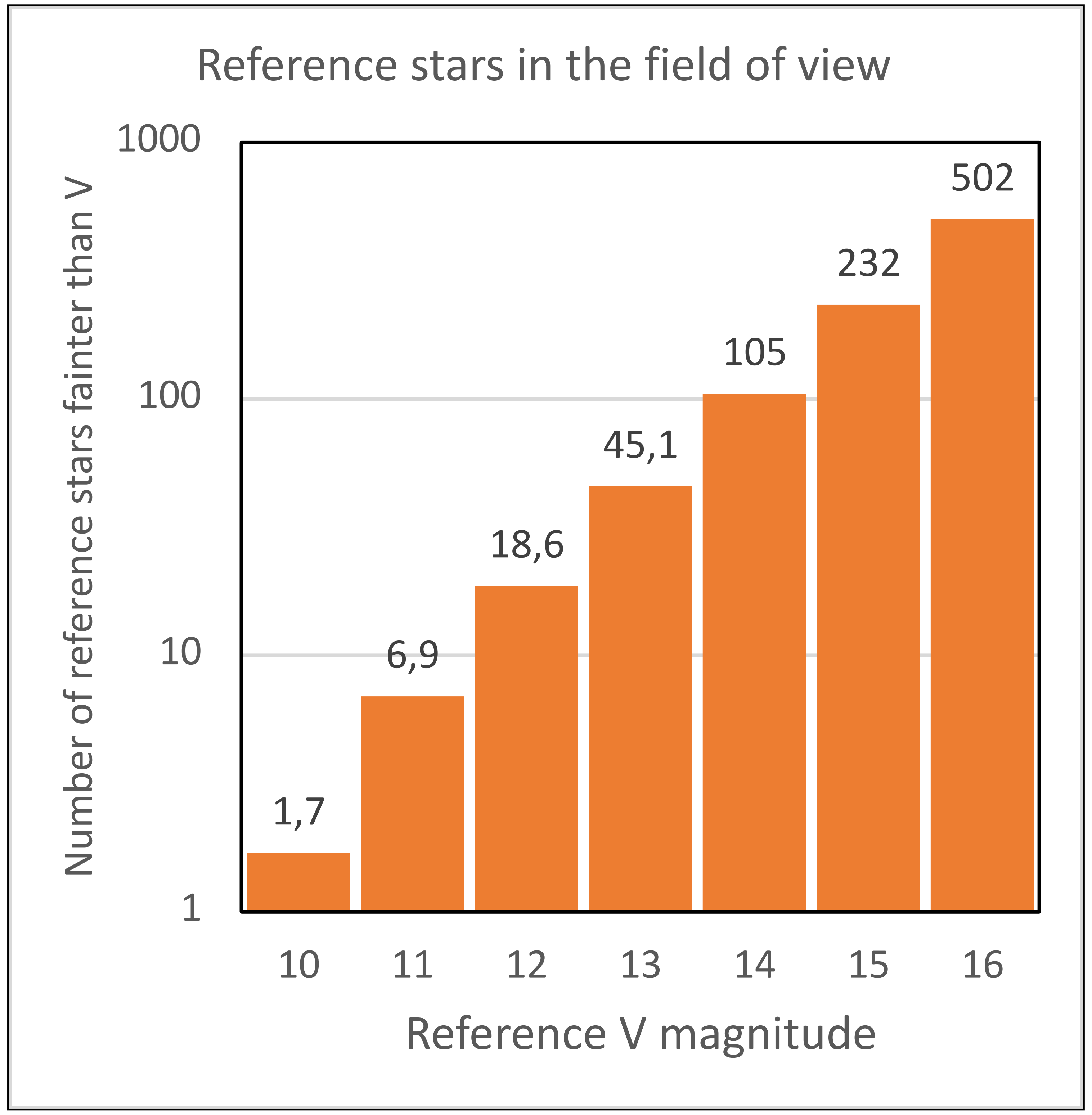


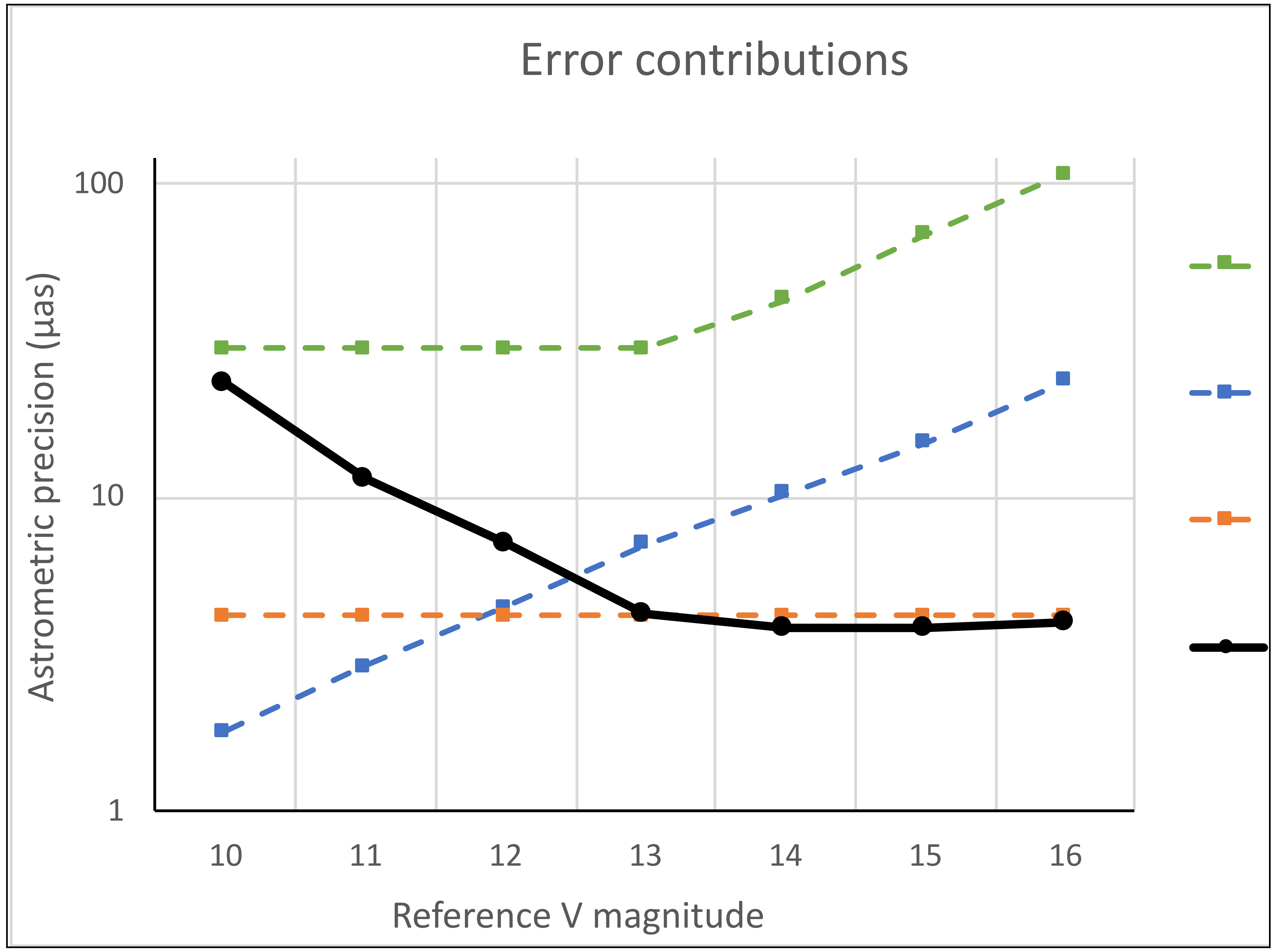
Contribution of the different errors

V	10	11	12	13	14	15	16
Nb of V ref stars	1,7	5,2	11,7	26,5	60	127	270
Cumulated Nb of (V'≤V) ref stars	1,7	6,9	18,6	45,1	105	232	502
σ_{ph} (µas)	1,8	2,9	4,5	7,1	10,3	15	23,7
σ_{det} (µas)	4,2	4,2	4,2	4,2	4,2	4,2	4,2
σ_{Gaia} (µas)	30	30	30	30	43	69	107
$\sigma_{Barycenter\_V}$ (µas)	23	13,3	9	6	5,7	6,3	6,7
$\sigma_{Barycenter\_V'\leq V}$ (µas)	23,2	11,5	7,1	4,25	3,82	3,83	4,01

The Gaia barycentric position $\boldsymbol{b}(t)$ is described by the following linear model :

$$\vec{b}(t) = \vec{b}_{ep} + (t - t_{ep})\vec{v}$$





$$\sigma_{GAIA}\left[\vec{b}_{ep} + (t - t_{ep})\vec{v}\right]$$

$$\sigma_{ph} = 0.42 \frac{f\lambda}{D} \frac{1}{\sqrt{N_i}}$$

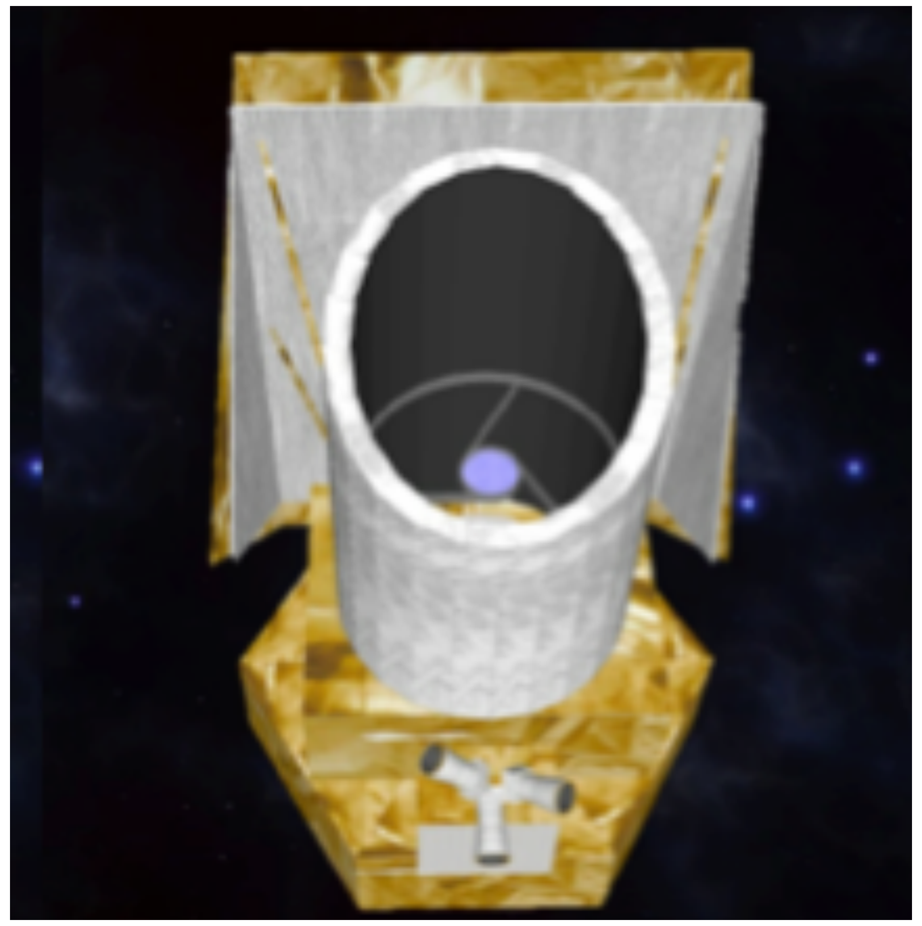
$$\sigma_{det} = 2.10^{-5}\text{px}$$

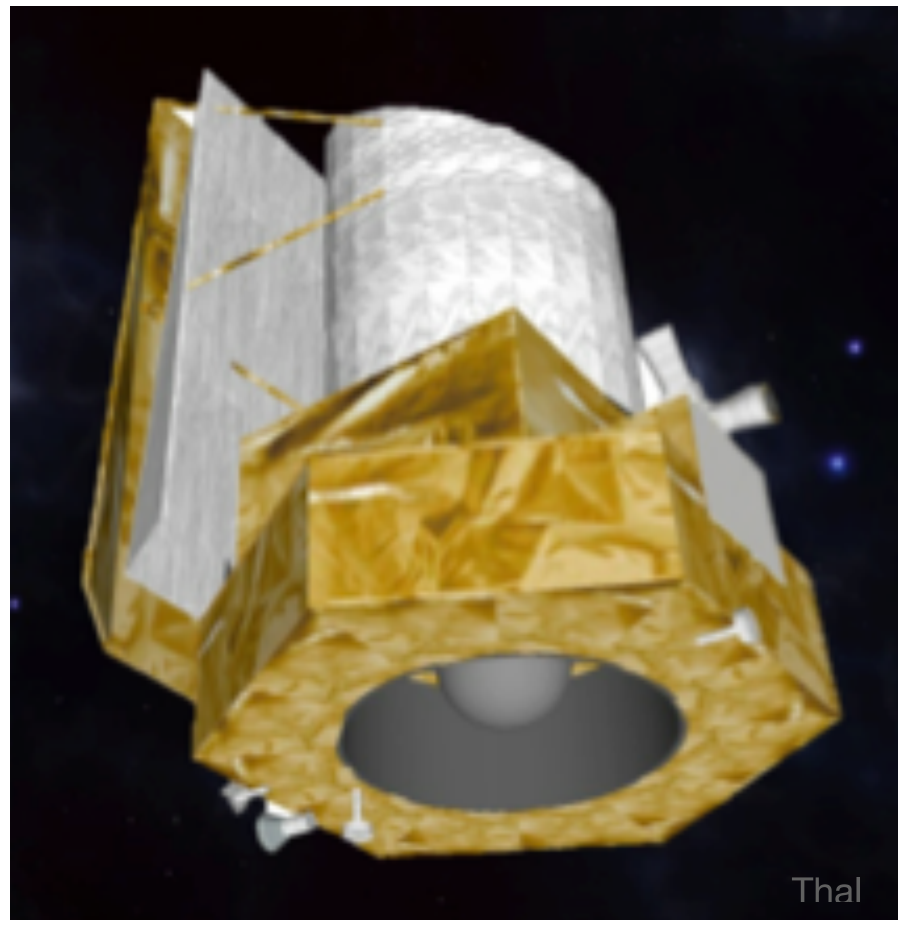
$$\sigma_{Barycenter} = \frac{1}{N}\sqrt{\Sigma_{refV\leq V}\ \sigma_V^2}$$

Theia mission profile

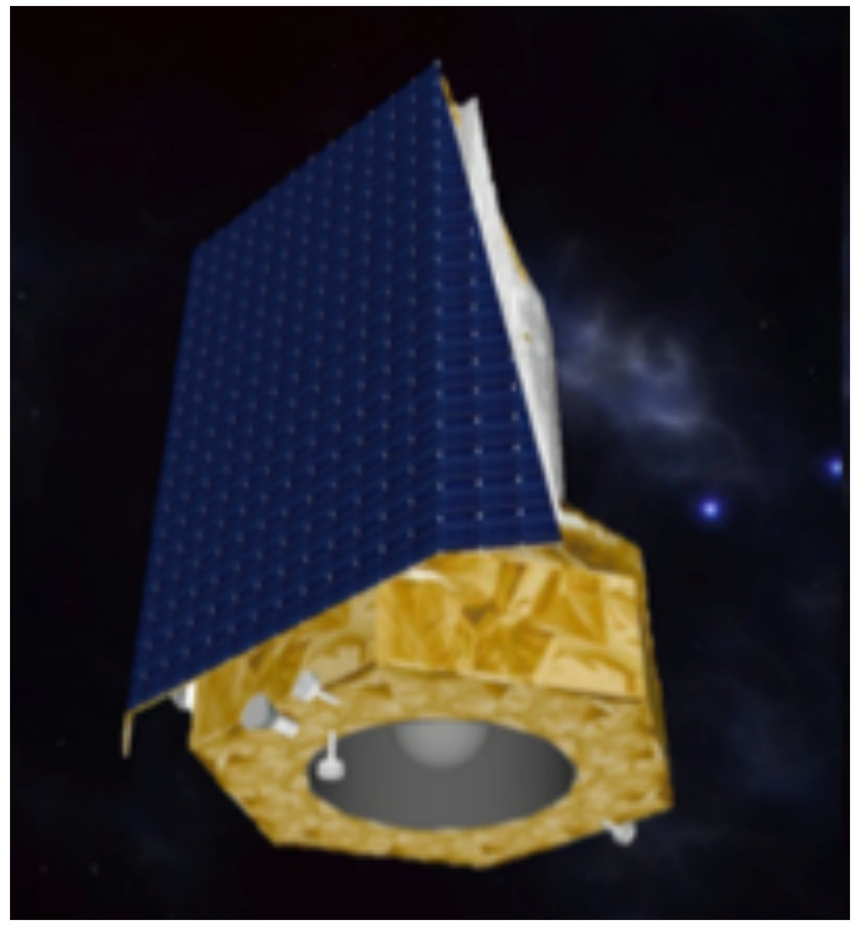
- **ESA-led, ESA-operated mission with consortium funded payload** (this is the normal type of ESA mission)
- Submitted for the **ESA M7 call** as an Ariane 6.02 launch
- Spacecraft dry mass with margin: 1063 kg. Total launch Mass: 1325 kg

Launch date	No constraints, allowing launch date in **2037**
Orbit	Large Lissajous in L2
Lifetime	• 4 years of nominal science operations • Tecnical operations: 6 months orbit transfer plus instrument commisioning and 1 month decomissioning
Concept	Single spacecraft, single telescope in the PLM, single camera in the focal plane, metrological monitoring of PLM
Communication architecture	75 Mbps, 4h/day



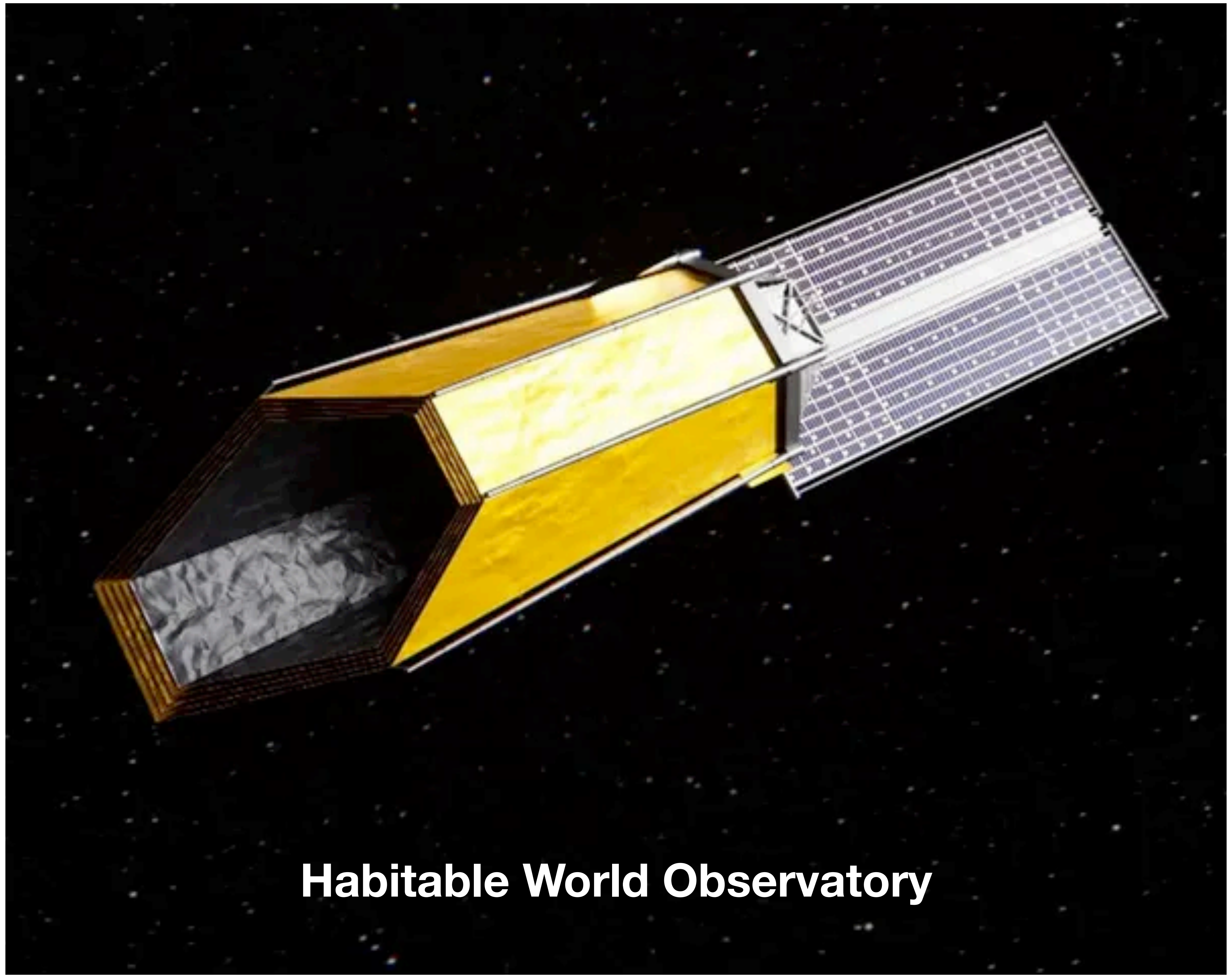


Thal



What about HWO wide field imager ?

- **Habitable World Observatory parameters**
  - Wavelength : UV, visible et IR
  - Diameter between 6.5 and 8 m
  - Launch foreseen for ~2040
  - PSF ~ λ/D = 14 mas, focal length ~130 m
  - exo-Earth signature @ 10pc : 0.3 µas
    Nyquist => signature ~ 5e-5 pixels
  - Field of view 2'x3' (TBC)
  - Detector size : 20 000 x 30 000 px ~ 1 Gpx
  - m_{target} ~ 6; $m_{ref} \leq$ 20 to get ~100 ref stars
  - Exposure time reduced by 100 / Thea



Conclusion and perspectives

- One of Theia most challenging science objectives is to identify planets down to the Earth mass (M ≤ 5 M_Earth) exoplanets in the habitable zone of Solar-type stars in the vicinity of the Sun (d ≲ 15 pc)
- Pointed differential astrometry allows the number of exposures to be increased compared to global astrometry allowing to reach sub-microarcsecond accuracy
- Technical challenges are the focal plane array and mitigation of the optical distortion of the telescope: new detectors and new calibration strategy are under investigation with lab test benches.
- Frequent calibrations ($\tau_{\text{exposure}} \sim 0.1$ s) with Gaia data reduces considerably telescope stability requirements
- How to cope with the Gaia error